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Safety situation forecast of mining system based on dynamic division of states

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Abstract

A forecast method of mining system safety situation is proposed based on dynamic division of states. On the basis of the number of total mine safety accidents, the boundary lines was determined according to the comparative analysis of residuals between estimated values based on seasonal index trend fitting model and actual number of total mine safety accidents, obtaining the dynamic division of transition states. Then weighed Markov forecast model under the influence of environment factors was built, by which, the safety situation of mining system was predicted. It was found that dynamic division can improve prediction accuracy, which enables the prediction model to better reflect the safety situation of mining system.

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Keywords: mining system; safety situation; dynamic division of states; weighed Markov; forecast

1. Introduction

Mining industry has been the focus area in safety production management in China. Safety situation forecast of mining system can provide effective basis for its safety management, investment and measures, which is a prediction of future safety changes based on the past and present state. So it is important to master and predict safety situation for mine safety management. However, due to the complexity and dynamics of mining system, forecasting results by conventional forecasting methods generally have such problems as poor fitting, low prediction accuracy, even

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deviation from actual direction due to the poor model, incomprehensive consideration, unreasonable division of states, data calculating error and so on[1-3]. Thus, appropriate safety situation forecasting method is the key of accurate prediction. Consequently, weighed Markov forecasting model has been established based on dynamic division of states with environmental aspects as weight factors.

2. Weighted Markov forecast for safety situation of mining system

To better reflect the overall system situation, this paper selects the number of total mine safety accidents as index parameter for safety situation. For the mining accidents data published by State Administration of Work Safety, especially the data from January 2007 to August 2013 counted by *Journal of Safety and Environment*, we take every two months as a time period. Then the 40 sets of data will form a time series , which defined as t_i=1,2,…, 40, while the number of total mining accidents occur in each time period defined as x_i(i=1,2, …, 40), obtaining mining accidents statistics of the time series as Table 1.

Table 1. Statistics of the number of total mining accidents.

t_i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
x_i	28	61	55	69	42	39	20	41	43	47	48	34	21	35	40	38	34	26	15	38
t_i	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
x_i	36	33	15	16	7	29	30	26	22	16	11	14	18	22	22	19	8	20	9	13

By analyzing historical data, it is acknowledged that the number of total mining accidents is discrete in timeline, which is in accordance with ineffectiveness characteristic of typical Markov chain of stochastic time series[1,2]. By identifying Markov chain state transition probability matrix at different lag time of safety situation of mining system, self-correlation coefficients r_k and weights of Markov w_k can be calculated through formula (1) and formula (2).

$$r_k = \frac{\sum_{i=1}^{n-k}\left(x_i - \bar{x}\right)\left(x_{i+k} - \bar{x}\right)}{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}, k \in \mathrm{E} \tag{1}$$

$$w_k = \frac{|r_k|}{\sum_{k=1}^{m}|r_k|}, m \in \mathrm{E} \tag{2}$$

Meanwhile, safety situation of mining system is affected by environmental factors, which include natural conditions, social environment, laws and regulations, enterprise management and working environment, so w_k above mentioned should be adjusted through

$$w' = w_i w_k \tag{3}$$

by $w_{i,}$, which is single scheduling weight of each environmental factor determined by using analytic hierarchy process[4-6]. Then the safety situation of mining system can be predicted by using weighted Markov chain prediction model[3,7]. However, Markov prediction accuracy is directly affected by the division of states[8,9]. In order to improve prediction accuracy, dynamic division of states is proposed to predict safety situation of mining system under environmental factors based on absolute index which is number of total mine safety accidents[2,3].

3. Dynamic division for states of mining system safety situation

3.1. Determination of seasonal trend model

As changing nonlinearly, randomly and periodically over time with t_i=1, 2…, 40, safety situation of mining system has been fit by nonlinear trend equation, obtaining a trend fitting equation. Then the number of mine safety accidents can be estimated through the trend fitting equation. With the correlation test between estimated results and actual number of total mine safety accidents, it is acknowledged that exponential function $T=51.819e^{-0.035t}$ is best for seasonal trend fitting.

For random time series $\{X_n, n \geq 0\}$, with elimination of trend effect, the seasonal index series can be described as $\{S_i : S_i = \frac{x_i}{T_i}, i = (1,2,\cdots,40)\}$. When season length $L_k = k+1, k \in [1.\infty)$, self-correlation coefficients can be calculated through

$$S_{ki} = \frac{S_i + S_{i+\frac{n}{k+1}} + S_{i+\frac{2n}{k+1}} + \cdots}{\frac{n}{k+1}} \tag{4}$$

before it cannot decide whether the development trend of safety situation of mining system has periodicity by variance analysis method[1]. Then we can get the seasonal index trend model as formula (5).

$$\hat{T}_i = T_i \cdot \prod S_{ki}, \quad k \in [1, \infty), i = (1,2,\ldots,40) \tag{5}$$

With the calculation of fitting degree for safety situation of mining system by seasonal index trend model, we get $R^2 = 0.8149$, which indicated that seasonal index trend model is applicable to the safety situation of mining system for trend fitting, whose cycle is 6. According to formula (5), it can be obtained that $\hat{T}_{41}$ is 13.

3.2. Dynamic division for system states

The sequence of estimated values by seasonal index model can be described as $\{\hat{T}_i, i = 1,2,\cdots,40\}$ while the actual number of total mine safety accidents as $x_i (i = 1,2,\ldots,40)$, which is shown in Fig. 1.

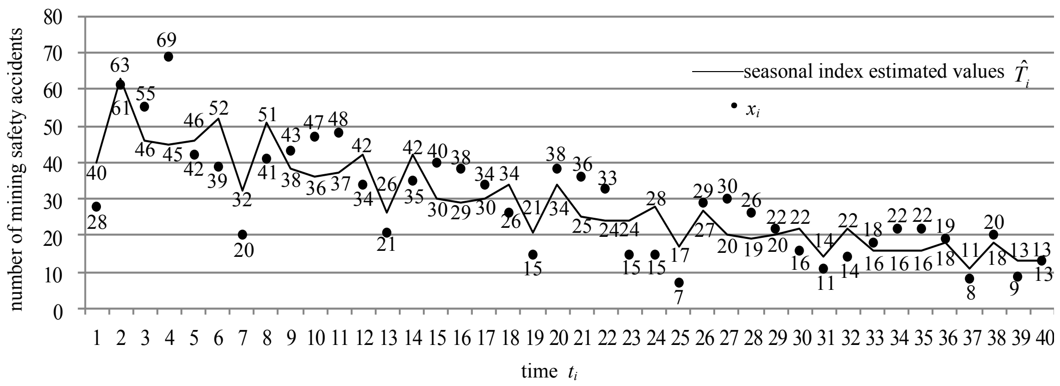

Fig. 1. Seasonal index trend.

According to the comparative analysis for residuals between estimated values based on seasonal index trend fitting model and actual number of total mine safety accidents, dynamic division boundary line of the state space was determined. With the maximum residual between seasonal index estimated values $\hat{T}_i$ and the number of total mine safety accidents x_i calculated as $A = \max\{\hat{T}_i - x_i\} = 13$, lower limit boundary line of state can be defined as $\hat{T}_A = \hat{T}_i - A$. Similarly, with the maximum residual between x_i and $\hat{T}_i$ calculated as $D = \max\{x_i - \hat{T}_i\} = 24$, upper limit boundary line of state can be defined as $\hat{T}_D = \hat{T}_i + D$. The number of total mine safety accidents can be counted as

q=20 below the seasonal trend line of safety situation of mining system in Figure 1. So the average residual between $\hat{T}_i$ and x_i can be calculated as $B=\frac{\sum_L \hat{T}_i - \sum_L x_i}{q} \approx 7$, consequently, the lower boundary line of state can be defined as $\hat{T}_B = \hat{T}_i - B$. Similarly, the average residual between x_i and $\hat{T}_i$ can be calculated as $C=\frac{\sum_H x_i - \sum_H \hat{T}_i}{p} \approx 7$, consequently, the upper boundary line of state can be defined as $\hat{T}_C = \hat{T}_i + C$.

The four areas between seasonal index estimation series $\{\hat{T}_i, i=1,2,\cdots,40\}$ and each boundary line are taken as state intervals of the number of total mine safety accidents, which are defined as E_m (m=1,2,3,4). If the number of total mine safety accidents x_i is between $\hat{T}_A$ and $\hat{T}_B$, then the transition state will be E_1, indicating that the safety situation of mining system have excellent development. If x_i is between $\hat{T}_B$ and $\hat{T}_i$, the transition state will be E_2, indicating that the safety situation is well developed. If x_i is between $\hat{T}_i$ and $\hat{T}_C$, then the transition state will be E_3, indicating that the safety situation is developed on average level. If x_i is between $\hat{T}_C$ and $\hat{T}_D$, then the transition state will be E_4, indicating that the safety situation is poor developed. As shown in Fig. 2.

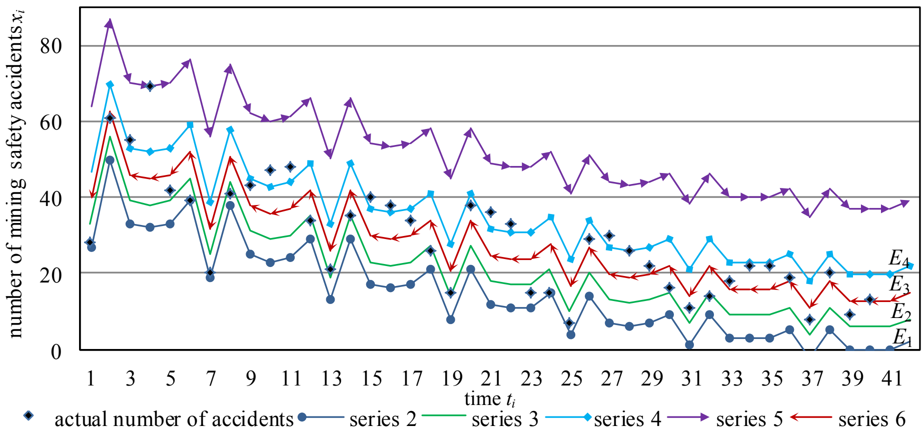

Fig. 2. Dynamic division of states.

3.3. State transition matrix

The frequency that forecasting object in random time series translates from state E_i to state E_j is defined as f_{ij}, $i,j \in m$, where m represents the number of states. Then we can get dynamic state transition frequency matrix from f_{ij} as formula (6).

$$f_{ij} = \begin{pmatrix} 4 & 3 & 3 & 0 \\ 2 & 2 & 3 & 2 \\ 1 & 3 & 3 & 3 \\ 2 & 1 & 2 & 5 \end{pmatrix} \tag{6}$$

Meanwhile, dynamic state transition probability matrix can be calculated by formula (7).

$$P_{ij} = \frac{f_{ij}}{\sum_{j=1}^{m} f_{ij}} = \begin{pmatrix} \frac{4}{10} & \frac{3}{10} & \frac{3}{10} & \frac{0}{10} \\ \frac{2}{9} & \frac{2}{9} & \frac{3}{9} & \frac{2}{9} \\ \frac{1}{10} & \frac{3}{10} & \frac{3}{10} & \frac{3}{10} \\ \frac{2}{10} & \frac{1}{10} & \frac{2}{10} & \frac{5}{10} \end{pmatrix} \tag{7}$$

4. Analysis of forecasting results

4.1. Markov property test

As marginal probability

$$p_{\bullet j} = \frac{\sum_{i=1}^{m} f_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{m} f_{ij}} \tag{8}$$

when n is sufficiently large, we can get statistic

$$\chi^2 = 2\sum_{i=1}^{m}\sum_{j=1}^{m} f_{ij} \left| \lg \frac{p_{ij}}{p_{\bullet j}} \right| \tag{9}$$

which is calculated as χ^2=2$\times$11.537=23.074. With a significance level given as α =0.5, so $\chi^2_\alpha(9)$=16.919, which meets the condition $\chi^2 > \chi^2_\alpha((m-1)^2)$, indicating that the time series, based on the dynamic division of states, is in accordance with the "Markov property". Consequently, it is reasonable to use Markov chain model to predict the safety situation of mining system.

4.2. Test of the forecasting accuracy

According to the number of total mining accidents x_i of the last six periods, the corresponding dynamic state transition probability matrix of and weights of environmental factors to mining system safety situation, weighted Markov chain model was used to predict the development trend of mining system safety situation of the next period. For t_i=41, it is calculated that the maximum weighted sum is 0.3504, in the state of E_3. So we can get the lower limit $\hat{T}_{41}$=13 and upper limit $\hat{T}_{C(41)} = \hat{T}_{41}$ +7=13+7=20, which means, at the point t_i=41, the estimated value of number of total mine safety accidents should be no less than 13, but no more than 20. Actually, the number of total mine safety accidents is 18. Consequently, it can be admitted that the weighed Markov forecasting for safety situation of mining system based on the dynamic division of states has excellent accuracy.

5. Conclusions

As mine safety system is a complex system, it is proper to use seasonal index trend model to fit the safety situation of mining system. Based on comparison of residuals between estimated values through seasonal index model and actual number of total mine safety accidents, the dynamic division of states for mining system safety situation has been established, which conform to the development trend of safety situation in mining system. Contemporary, with the consideration of environmental factors, weighed Markov forecast model with weights modification has been established, which can improve the prediction accuracy for mining system safety situation of next stage, providing basis for macro security management.

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